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THE RESULTS OF PHOTOGRAPHIC PHOTOMETRY OF JUPITER

Yu. V. Aleksandrov

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ABSTRACT. The optical parameters of the visible surface of Jupiter were studied through photographic photometry measurements made at the hark of Kahr'kov Astronomical Observatory between 1933 and 1959. A system of equations was derived to determine the optical parameters of the atmosphere and the surface of the planet by observing the smallest values of the phase angle. The method is based on an approximation of the observed and theoretical distributions of the brightness of the planetary disk.

A large number of photographs of Jupiter were made with the aid of light filters at the Kahr'kov Astronomical Observatory in 1932-1939 by N. P. Barabashov [1-3], in 1951-1954 by V. N. Lebedinets [4] and in 1951-1959 by A. T. Chekirda. The photographs of 1933, 1935, 1938, and 1939 were newly scanned photometrically in 1954 by V. N. Lebedinets with the aid of the MF-2 microphotometer [4]. These photographs showed brightness distributions along the light zones and the dark belt of Jupiter which he obtained in 1951-1954. The photographs obtained by A. T. Chekirda were measured with the aid of the MF-2 microphotometer by the author. The characterisitc curve of the photographic film was plotted from 10 marks obtained with the aid of a tubular photometer, and two calibration scales were applied on each film for measurement. The main three light zones and the two dark belts visible on the Jovian disk were measured through 0.1 mm. The scale of the photographs was 9" in 1 mm, and the size of the photometer aperture was 0.05 mm × 0.05 mm. As a rule the two best-quality images on two films for each year and each light filter were subject to measurement. A total of 350 brightness distribution curves was obtained. The total number of relative brightness distributions across the Jovian disk at our disposal in shown in Tables 1 and 2. /30*

*Numbers in the margin indicate pagination in the foreign text.

TABLE 1.

Filter	$\tilde{\lambda}_{m\mu}$	Years 1933	1935	1938	1939	1951	1952	1953	1954
Blue	432	—	—	—	—	1/1	1/1	3/2	3/2
	460	3/2	3/2	2/3	2/3	—	—	—	—
Green	521	—	—	—	—	—	—	3/2	3/2
Yellow	594	3/2	3/2	—	—	1/1	1/1	3/2	3/2
Red	648	3/2	—	2/3	2/2	1/1	1/1	3/2	3/2

TABLE 2.

Filter	$\tilde{\lambda}_{m\mu}$	Years 1951	1952	1954	1957	1958	1959
Blue	432	12/8	6/4	9/6	12/8	6/4	9/6
Green	521	—	12/8	12/8	12/8	9/6	12/8
Yellow	594	12/8	6/4	12/8	6/4	12/8	—
Red	648	12/8	9/6	3/2	12/8	12/8	9/6

In these Tables the numerator designates the number of brightness distributions along the light zones, and the denominator designates those along the dark belts. In Table 1 each brightness distribution was obtained by averaging the results of the measurements of 3-5 planetary images and was interpolated graphically to points situated at distances of 0.05 of the equatorial radius of Jupiter.

The information obtained on the basis of the photometric scanning of approximately 190 images of Jupiter is utilized in this manner. This observational material in principle permits us to solve the inverse problem of radiation transfer in the atmosphere of Jupiter, i.e., to determine the optical parameters of various formations visible on the planetary disk. However, the usual method of least squares leads in the given case to a poorly related system of normal equations. This occurs in view of the smallness of the values of the α phase angle of Jupiter. The method of preliminary parabolic approximation of observed and theoretical distributions of brightness by means of Chebyshev polynomials, proposed in [12], allows us to establish the /31 maximum possible number of parameters of a theoretical model of the atmosphere; these may be determined in accordance with observational data. In the case of the relative surface photometry of Jupiter this number equaled two. Thus it is necessary to select a model of the atmosphere, fully defined by two parameters, which at the same time can more or less correctly reflect physical reality. We accepted a semi-infinite absorbent atmosphere with an indicatrix of scattering

$$x(\gamma)=1+x_1P_1(\cos\gamma)+x_2P_2(\cos\gamma), \tag{1}$$

where P_1 and P_2 are Legendre polynomials, γ is the scattering angle. A general solution of the problem of diffused light reflection of a semi-infinite atmosphere with indicatrix of scattering (1) with true absorption was given in [5]. An approximate solution in final form in the case $x_2 = 0.5$ and with low true absorption (survival probability of quantum λ near 1) was derived in [13]. Below are shown approximation formulas obtained in a similar manner for reflected light intensity with arbitrary x_2 and λ near unity (terms of the order of $\sqrt{1-\lambda}$ were retained).

$$\begin{gathered}
I(\eta,\zeta,\varphi-\varphi_0)=\frac{\lambda s\zeta}{4(\eta+\zeta)}[F^{(0)}(\eta,\zeta)+\\
+F^{(1)}(\eta,\zeta)\sqrt{(1-\eta^2)(1-\zeta^2)}\cos(\varphi-\varphi_0)+\\
+F^{(2)}(\eta,\zeta)(1-\eta^2)(1-\zeta^2)\cos 2(\varphi-\varphi_0);\\
F^{(0)}(\eta,\zeta)=-x_1\chi(\eta)\chi(\zeta)+\frac{3x_2}{4+x_2}\varphi(\eta)\varphi(\zeta)+\\
+\frac{3}{4(4+x_2)}\psi(\eta)\psi(\zeta);\\
\chi(\eta)=p\eta\frac{1+\sqrt{3}\eta}{1+k_0\eta};\ \varphi(\eta)=\eta(1-p+k_0\eta)\frac{1+\sqrt{3}\eta}{1+k_0\eta};\\
\psi(\eta)=\left[\frac{4+x_2}{\sqrt{3}}-\eta\left(x_2+\frac{4x_1}{\sqrt{3}}p+x_2k_0\eta\right)\right]\frac{1+\sqrt{3}\eta}{1+k_0\eta};\\
p=\frac{4+x_2}{4}\frac{\sqrt{3}k_0}{3-x_1};\ k_0^2=(1-\lambda)(3-x_1);
\end{gathered} \tag{2}$$

$$
\begin{aligned}
&F^{(1)}(\eta, \zeta)=x_1\Theta(\eta)\Theta(\zeta)-3x_2\sigma(\eta)\sigma(\zeta);\\
&\Theta(\eta)=\left[1-\frac{3}{2}x_2\frac{(3-x_1)\eta}{4(2+R_1)-3x_1}\right]\frac{1+2\eta}{1+k_1\eta};\\
&\sigma(\eta)=\frac{4}{3}\,\frac{(3-x_1)(2+k_1)\eta}{4(2+k_2)-3x_1}\,\frac{1+2\eta}{1+k_1\eta};\\
&k_1^2=4-\frac{3}{2}\left[x_1+\frac{3x_2(3-x_1)}{4}\right];\\
&F^{(2)}(\eta, \zeta)=\frac{3x_2}{4}H^{(2)}(\eta)H^{(2)}(\zeta);\\
&H^{(2)}(\eta)=\frac{1+2\eta}{1+k_2\eta};\ k_2^2=4-\frac{27}{32}x_2.
\end{aligned}
\tag{2}
$$

Here πS is illuminance of the area situated at the boundary of the /32
atmosphere, normal to incident light; η and ξ are cosines of the angles of light reflection and incidence; $\phi - \phi_0$ is the difference in azimuth of reflected and incident light. In order to obtain formula (2) subsidiary approximation integral equations for function $H^{(0)}(\eta)$ in an Eddington approximation, and the Shuster-Shwarzschild approximation was solved for functions $H^{(1)}(\eta)$ and $H^{(2)}(\eta)$. An approximation formula was also derived [14] for the spherical albedo of a planet surrounded by such an atmosphere.

$$A_c=1-(4+x_2)\sqrt{\frac{1-\lambda}{3-x_1}}. \tag{3}$$

Based on polydispersed indicatrices of light scattering calculated in [15] on semi-transparent particles, the dependence between coefficients x_1 and x_2 was obtained, which pertains only to the aerosol component of the indicatrix of scattering. However, with x_1 values from 0 to 2 it may be approximated by the function $x_2 = 0.5 + 0.25\,x_1$, and this form of the dependence between x_1 and x_2 is also maintained for a "gas + aerosol" mixture. Thus two parameters remain to be determined: x_1, the "elongation" of the indicatrix of scattering and λ, the quantum survival probability, or the ratio of the coefficient of scattering to the sum of the coefficients of scattering and true absorption. The assumption of the proximity of λ to 1 in the model accepted follows as a result of the high ($\geqslant 0.5$) value of the spherical albedo of Jupiter [14].

In agreement with [12] for all observed brightness distribution curves preliminarily reduced to the value $\alpha = 0$, the values b_1^e and b_2^e were calculated, which represent coefficients of the following presentation for relative brightness distribution:

$$I(I_0S)^{-1} = 1 + b_1u + b_2u^2, \tag{4}$$

where $u = r^2 + 0.4375$, and r is the relative distance from the center of the disk. This selection of argument u is associated with the fact that where $\alpha = 0$ the brightness distribution is an even function of the distance from the center of the disk, and the shift by 0.4375, i.e., to the point with $\eta = 0.75$ is made so that the polynomial (4) better approximates the value I where $0 < \eta < 0.5$. The values I_0, b_1 and b_2 were also tabulated [14] as four functions λ and x_1 for the model of the atmosphere which we accepted. Having integrated the value ηI across the planetary disk, we obtain the following expression for the geometrical albedo of the planet: /33

$$A_r = I_0(1 + 0{,}062\ b_1 - 0{,}164\ b_2). \tag{5}$$

With the aim of clarifying the dependence of the parameters desired on the wavelength of light and on time of observation, a two-factor analysis of variance of obtained values b_1^e and b_2^e was made which shows that with a level of significance of 0.95 possible spectral variation in the green-red region and possible changes with time with all filters were within the limits of measurement error.

The values finally accepted for coefficients b_1^e and b_2^e and the confidence intervals for these values are given in Table 3.

TABLE 3.

$\tilde{\lambda}$	Light zones				Dark belts			
	b_1^e	Δb_1^e	b_2^e	Δb_2^e	b_1^e	Δb_1^e	b_2^e	Δb_2^e
460—650 mμ	—1,055	±0,24	—0,515	±0,051	—0,962	±0,032	—0,544	±0,058
430 mμ	—1,055	±0,024	—0,234	±0,81	—0,962	±0,032	—0,284	±0,092

Table 4 shows optical parameter values λ and x_1 which correspond to the data in Table 3, and Figure 1 shows confidence ellipses which characterize the indefiniteness of determined values λ and x_1.

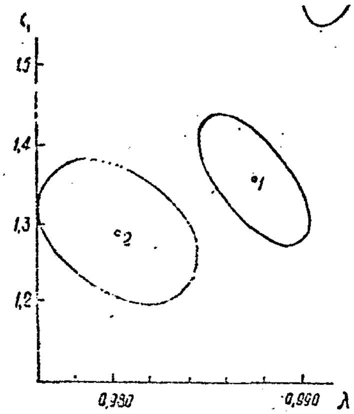

Figure 1. Confidence Ellipses for Parameters λ and x_1.

TABLE 4.

$\tilde{\lambda}$	Light zones		Dark belts	
	λ	x_2	λ	x_1
460—650$m\mu$	0,987	1,36	0,980	1,29
430$m\mu$	1,000	0,6	0,998	0,7

In view of the fact that a number of simplified assumptions were made /34 in connection with solving the problem, first of all it is necessary to check the result obtained by comparison with other observational data. Figure 2 shows the spectral behavior of the geometrical albedo of Jupiter A_{geo} [6] (curve 1), and values A_{geo} found according to the observed brightness distribution and the coefficient of brightness of the center of the Jovian disk, obtained in [4] (curve 2). The dashed area 3 indicates values of the geometrical albedo calculated according to determined values λ and x_1, with consideration for their indefiniteness. In this connection in the second and third cases the value A_{geo} was determined according to formula (5), and a value was taken which was an average of values for light and dark regions. Considering that the solution which we obtained was based on approximations, we may consider that the optical parameter values of the atmosphere of Jupiter agree with integral photometry data in the long-wave portion of the spectrum (500-650 mμ). In connection with the determined values λ and x_1, the contrast between the light zones and the dark bands must amount to 0.12, and the average value of observable contrast is $0.^m10$. The neutrality of the optical properties of Jupiter in this region of the spectrum is also confirmed by the result of Ye. L. Krinov [7], according to whose data the average spectral coefficient of brightness over the disk within the limits 490-650 mμ remains a practically constant value. An essential divergence occurs in the blue portion, where the reflectivity of Jupiter differs qualitatively from that which we obtained. Apparently the accepted model of the atmosphere in this portion of the spectrum already proves to be unsatisfactory; first of all the atmosphere must not be considered to be optically homogeneous in altitude, as assumed in the model examined above. In order to check this proposition a model of a two-layer atmosphere (a very rough one, of course) was examined on the basis of a formula from [8, Chapter VII]:

$$IS^{-1} = A\zeta^{q} e^{-\frac{2\tau}{\zeta}} + 0{,}188\left(1 - e^{-\frac{2\tau}{\zeta}}\right), \qquad (6)$$

in which in place of the term $A\xi^q$, which characterizes the law of reflection from an underlying surface, intensity values of reflected radiation were introduced, calculated for the model of the atmosphere under consideration. Thus it is assumed that above the semi-infinite gas-aerosol atmosphere there is an optically thin layer of gas, which scatters light in accordance with the Rayleigh law. It appeared that with values for light zones $\tau = 0.1 - 0.2$; $x_1 = 1.2 - 1.5$ and $\lambda = 0.974 - 0.984$ and for dark belts $\tau = 0.10 - 0.20$; $x_1 = 1.3 - 1.5$; $\lambda = 0.982 - 0.990$ within the limits of observational errors, observed and calculated albedo values may agree. It follows from this that above the Jovian cloud layer there is located a layer of gas of sufficient depth to have a noticeable influence on the optical properties of the planet in blue light, but the accuracy of observations at the present time does not yet permit a more decisive evaluation of the parameters of this gaseous layer.

The phase function for Jupiter (see Table 5) is found by means of the relationship obtained by V. V. Sobolev [9] between the planetary phase function and the parameters λ and x_1. /35

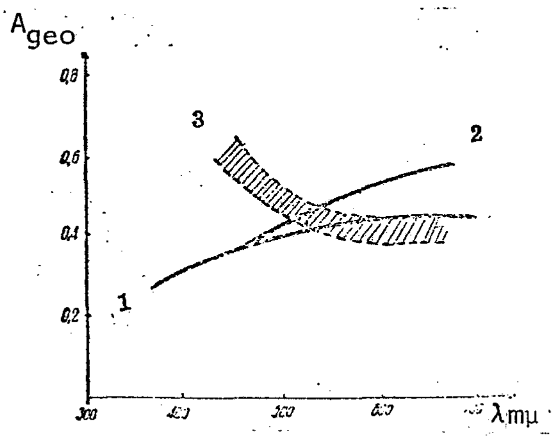

Figure 2. The Spectral Behavior of the Geometrical Albedo A_{geo} of Jupiter. 1, after D. L. Harris; 2, after V. N. Lebedinets; 3, range of values A_{geo} which correspond to determined values λ and x_1.

TABLE 5.

α	0°	15°	30°	45°	60°	75°
$\Phi(\alpha)$	1,000	0,958	0,854	0,725	0,580	0,447
α	90°	105°	120°	135°	150°	165°
$\Phi(\alpha)$	0,329	0,227	0,149	0,084	0,035	0,010

For further interpretation of the optical parameter values obtained, we shall consider that the gaseous components scatters light in accordance with the Rayleigh law. Then

$$x_1 = \frac{k_{pa} x_{1a}}{k_{pR} + k_{pa}}, \tag{7}$$

where k_{pa} and k_{pR} are scattering coefficients of the aerosol and gaseous components of the atmosphere.

The Rayleigh scattering component in gases, as is known, has the form

$$k_{pR} = \frac{24\pi^3 \mu \delta_2 R^2_{gas}}{N_A \tilde{\lambda}^4}, \tag{8}$$

where δ_{gas} and μ are density and molecular weight of the gas; N_A is the Avogodro number; R_{gas} is gas refraction.

The scattering coefficient per unit volume of the aerosol component of the atmosphere may be presented in the form:

$$k_{pa} = cN\delta_a^2 \tilde{\lambda}^2 R_a^2 k_{pa}^* (\tilde{\lambda}, \bar{a}_g, \sigma^2). \tag{9}$$

Here N is the number of aerosols per unit volume; δ_a is the density of matter forming the aerosols; R_a is the refraction of this matter; k_{pa}^* is a value tabulated in work [15] for particles of water in air; the coefficient c is associated with the transition from the optical characteristics of water to the characteristic (of refraction) of a given substance.

Substituting (8) and (9) in (7), after certain transformations we obtain:

$$p = C\tilde{\lambda}^6 k_{pa}^* \left(\frac{x_{1a}}{x_1} - 1\right), \tag{10}$$

where p is a certain parameter which characterizes the properties of the atmosphere;

$$p = \frac{\mu\delta_{gas}}{N\delta_a^2}\left(\frac{R_{gas}}{R_a}\right)^2, \tag{11}$$

coefficient $C = 0.0211\ g^{-1}$. The values k_{pa}^* and x_{1a} are tabulated in [15] as functions of the length of light wave λ, of the average geometrical aerosol dimension a_g and of the dispersion of their distribution according to dimensions σ^2. The relationships $p = p(a_g)$ in connection with values $\sigma^2 = 0.5$ and values x_1 obtained above are shown in Figure 3. In establishing now the form of the dependence $p = p(\tilde{\lambda})$, we may find the values $\bar{a}_g$ and p. The proximity of intersecting points of the curves in Figure 3 make the assumption a natural one that in the portion of the spectrum examined, $p(\tilde{\lambda})$ = const. Then we find that $a_g = 0.075 \pm 0.010$, $p = 0.011 \pm 0.006\ g^{-1}cm^6$. A value which is an average one for the light and dark regions is taken since the differences in values x_1 here fall within the limits of observational error. Knowing a_g we find x_{1a}, and then, using (7) and the determination of value λ, we find that the aerosol albedo λ_a (see Table 6) equals /36

$$\lambda_a = \left[1 + \frac{x_{1a}}{x_1}\left(\frac{1}{\lambda} - 1\right)\right]^{-1}. \quad (12)$$

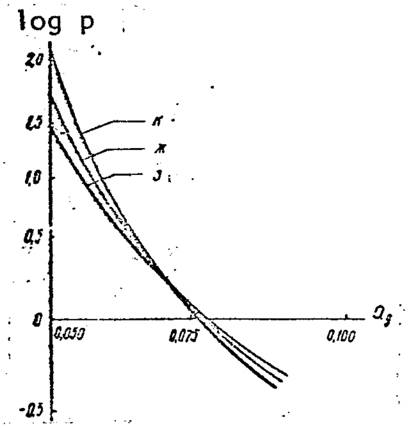

Figure 3. The Spectral Behavior of Values of Parameter p Which Characterizes the Atmosphere of Jupiter.

TABLE 6.

$\lambda m\mu$		521	594	648
x_{1a}		2,12	1,95	1,86
λ_a	Zones	0,979	0,981	0,982
	Belts	0,969	0,971	0,972

Accepting that within the limits of observational errors, the scattering properties of aerosols in zones and belts are identical, we find the ratio of the coefficients of absorption in zones and belts the difference of which also specifies the observable contrast of light zones and dark belts. The value $\frac{k_{ab\ belt}}{k_{ab\ zone}} = 1.56$. We note that in agreement with [10] the degree of polarization of light for zones and belts also reveals no systematic difference and significant spectral behavior.

The optical depth of a homogeneous, purely gaseous atmosphere is

$$\tau = k_{pR} H, \quad (13)$$

in which height

$$H = \frac{P}{\delta_{gas} g}, \quad (14)$$

where P is pressure; g is acceleration of the force of gravity. Considering (8), we find that

$$\tau = \frac{24\pi^3 R_{gas}^2 \mu}{N_A \lambda^4 g}. \quad (15)$$

In agreement with V. I. Moroz [11], the pressure at the lower boundary of the cloud layer P = 2 atm, and the layer above the clouds mainly consists of hydrogen and helium in approximately equal quantities. For $\tilde{\lambda}$ = 589 mμ the refraction of hydrogen R_H = 1.04, and helium R_{He} = 0.13, which leads to the value τ_{589} = 0.046. From the evaluation obtained above for τ_{430} it follows that $0.02 < \tau_{589} < 0.05$, which agrees with the determined value τ_{589}. /37

For a further refinement of the structure of the Jovian atmosphere, and in order to obtain more exact evaluations of its optical parameters and more reliable interpretations of them, additional material is required and it is necessary to conduct simultaneous integral and absolute surface photometry of Jupiter by the photoelectric method with narrow-band light filters in a wide range of wavelengths, including the ultraviolet and the infrared region, in those portions of the spectrum as free as possible from absorption bands.

It is necessary to obtain brightness distribution as close as possible to the limb of the disk, for at distances of 0.15 of the radius of the planetary disk, which cannot be measured photometrically on photographs, we lose up to half of the information which is contained in the brightness distribution curve.

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